SHORT RANGE STRUCTURE OF CLOUDS

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Scales and Scaling in the Climate System:

Bridging theory, climate models and data

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WHY ARE WE INTERESTED IN CLOUDS?

- Clouds exert ***strong radiative influence*** in shortwave (– 48 W m^{-2}) and longwave (+ 17 W m^{-2}) global average; much more locally and instantaneously. Even thin clouds exert strong radiative effects.
- Need to accurately represent clouds in weather and climate models.
- Any change in clouds could augment or diminish the climate impact of increasing greenhouse gases – ***cloud feedbacks***.
- Clouds may be visible manifestation of ***atmospheric dynamics and variability***.
- Cloud-aerosol interactions and ***radiative forcing of climate change***.

WHAT IS A CLOUD?

AMS Glossary of Meteorology (2000)

A ***visible aggregate*** of minute water droplets and/or ice particles in the atmosphere above the earth's surface.

Total cloud cover: Fraction of the sky hidden by all ***visible clouds***.

Clothiaux, Barker, & Korolev (2005)

Surprisingly, and in spite of the fact that we deal with clouds on a daily basis, to date there is ***no universal definition of a cloud*** . . . . Ultimately, the definition of a cloud ***depends on the threshold sensitivity*** of the instruments used.

Ramanathan, JGR (ERBE, 1988)

Cloud cover is a ***loosely defined term***.

Potter Stewart (U.S. Supreme Court, 1964)

I shall not today attempt further to define it, but ***I know it when I see it***.

CLOUD OPTICAL DEPTH, τ

Vertical integral of scattering coefficient σ.

Scattering coefficient σ is probability of photon being scattered per unit distance.

For cloud drops (radius r >> wavelength of light), $\sigma = 2\,\pi r^2\, n$ (n is number concentration of cloud drops).

Optical depth τ is commonly used measure of radiative influence of a cloud.

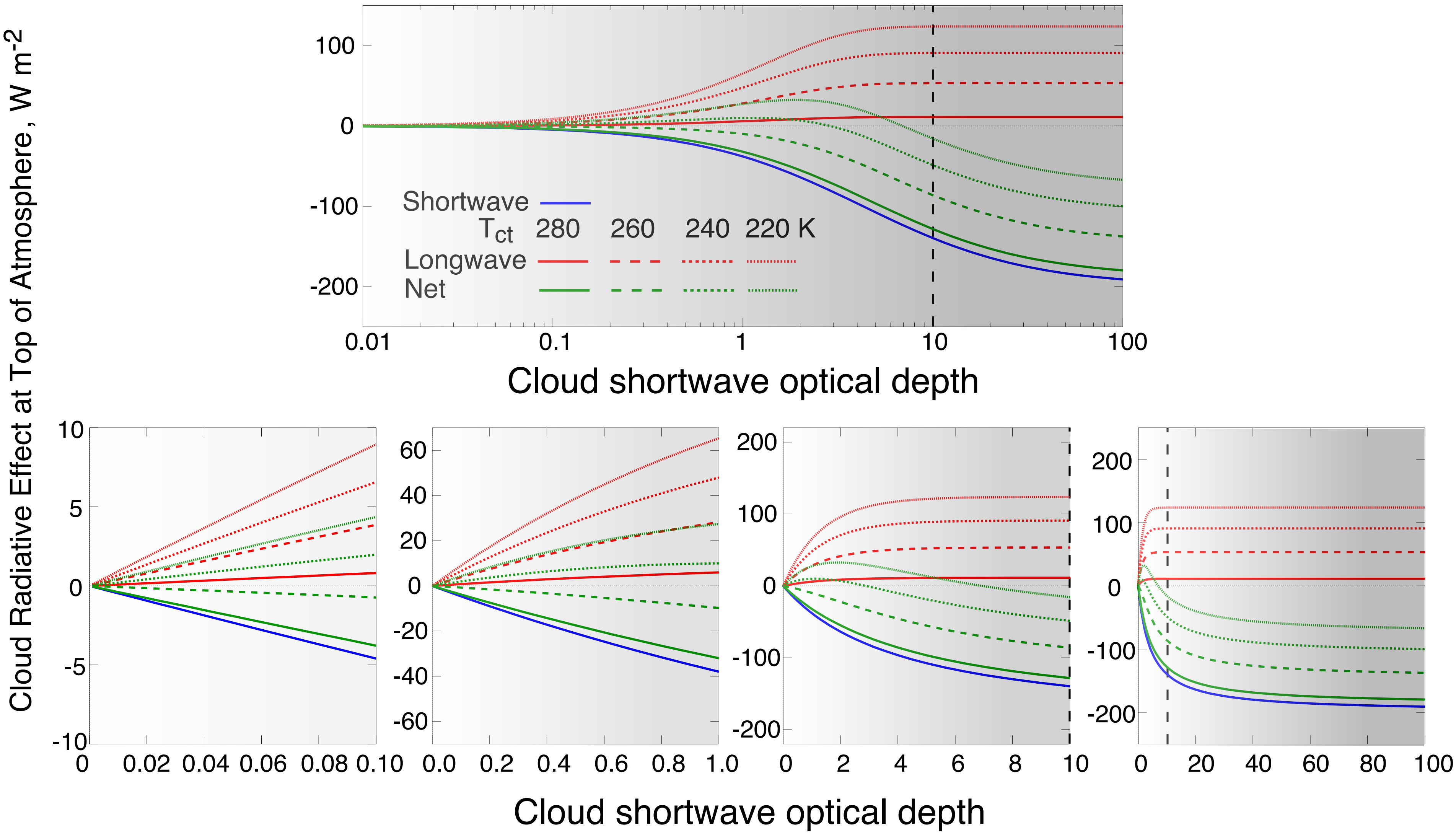
Thick clouds, $\tau \gtrsim 100$: Almost all light is scattered upward.

Thin clouds, $\tau \lesssim 1$: Most light is transmitted.

CLOUD RADIATIVE EFFECT

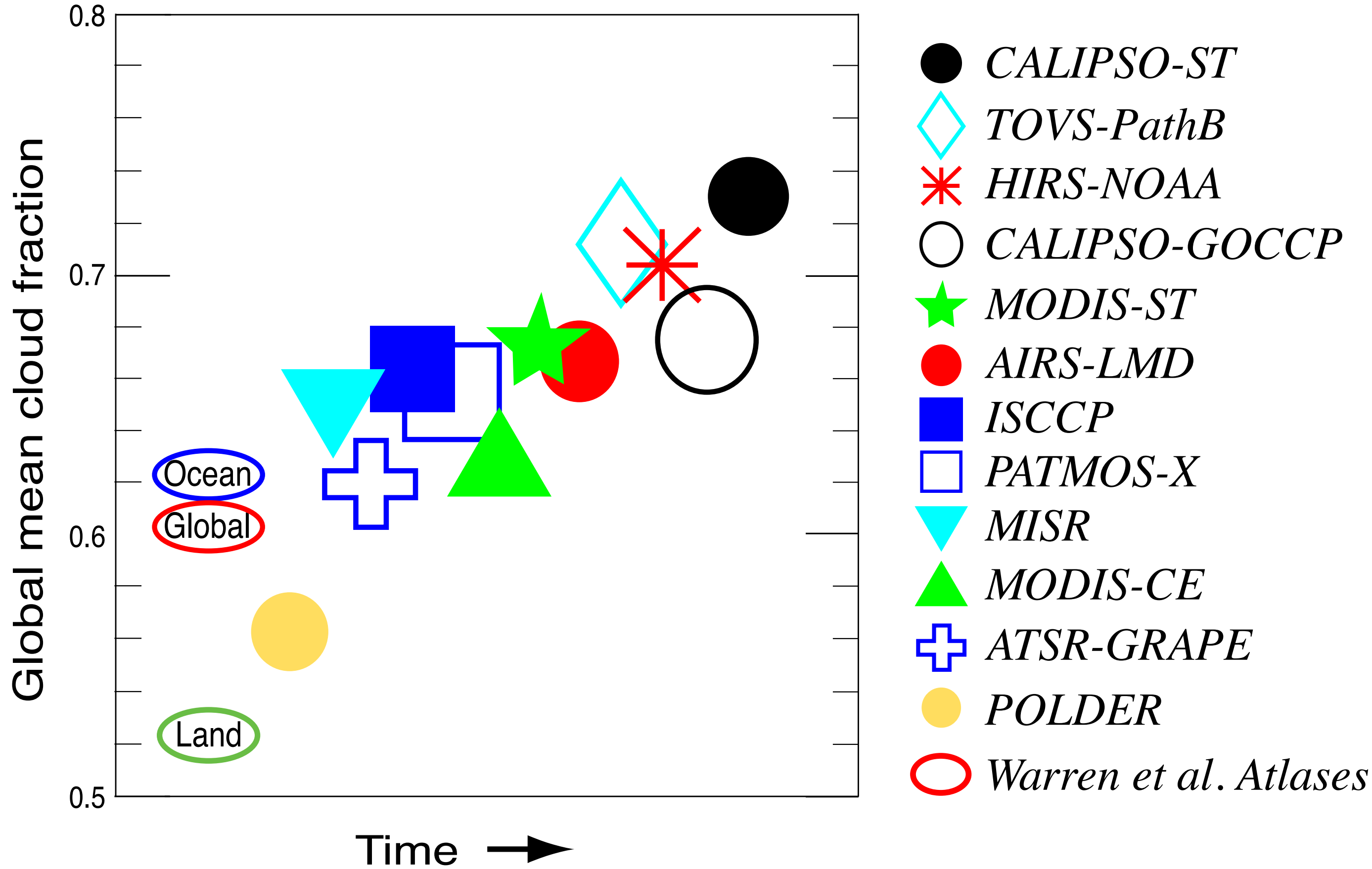
Dependence on shortwave optical depth and cloud-top temperature

24-Hour average CRE, north central Oklahoma, at equinox



Net CRE depends on optical depth and cloud-top temperature ***even in sign***.

MEASUREMENTS OF GLOBAL CLOUD FRACTION



Modified from Stubenrauch, Rossow, ...Ackerman, ...Chepfer, DiGirolamo, ...Winker et al., BAMS, 2013

- For clouds with optical depth > 0.1 global cloud fraction is about 68%.
- Cloud fraction increases to 73% when including subvisible cirrus with optical depth down to 0.01 (e.g. CALIPSO) and decreases to about 56% for clouds with optical depth > 2 (e.g. POLDER).
- Key reasons for differences: ***resolution*** and ***threshold***.

CHALLENGES IN CHARACTERIZING CLOUDS AND REPRESENTING THEM IN MODELS

- ***Ephemeral***. Clouds are tenuous, hard to define, harder to study.

  Condensed cloudwater is about 1% of surrounding water vapor.

  Cloudwater amount is highly dependent on condensation or evaporation associated with cloud vertical motion.

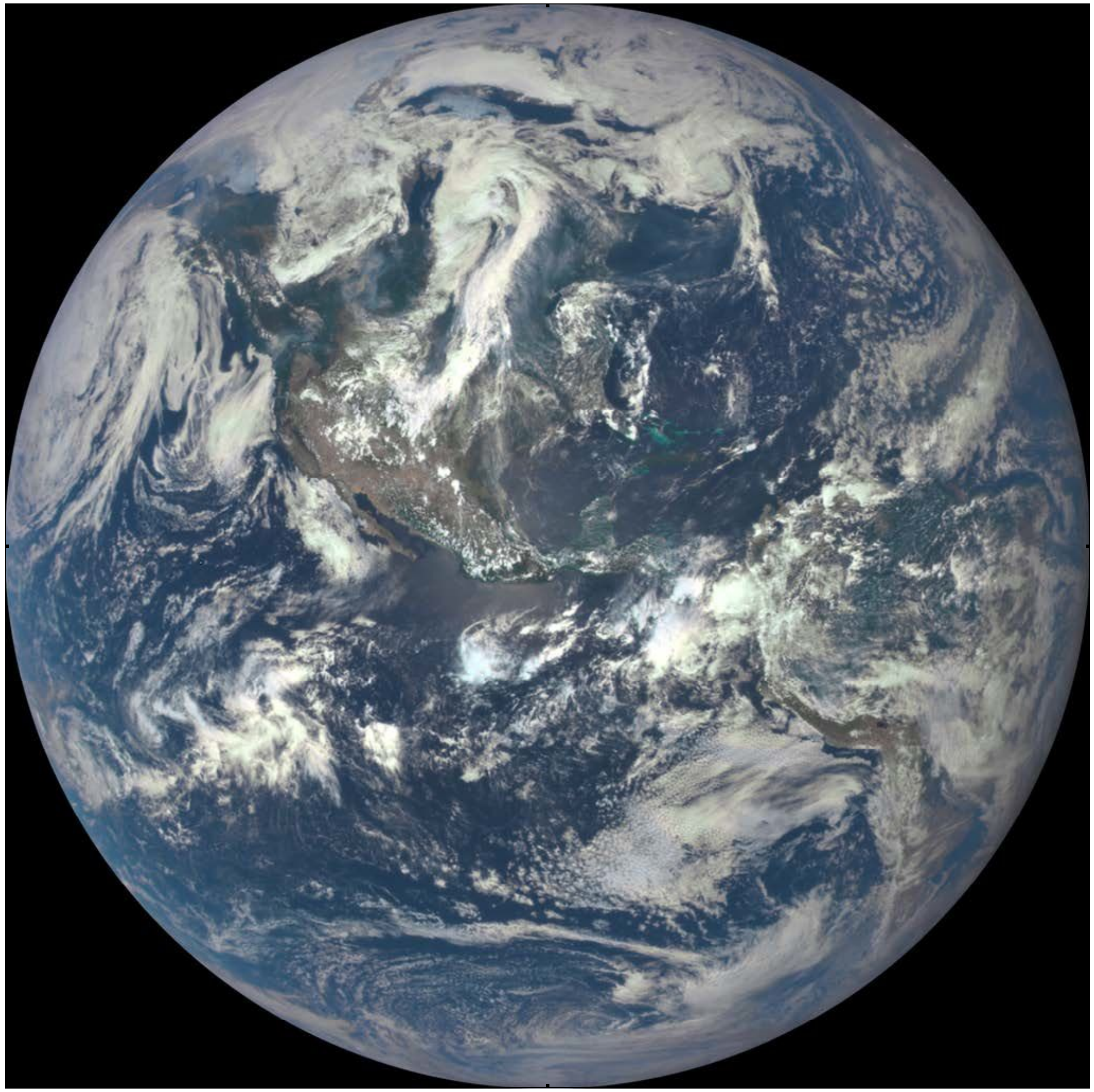
- ***Multiple scales***. Clouds exhibit structures on many scales, from thousands of kilometers down to 1 meter.

New methods of characterizing clouds are welcome.

CLOUD PHOTOGRAPHY FROM SPACE LOOKING DOWNWARD

EARTH FROM 1.5 MILLION KILOMETERS

DSCOVR satellite at Earth–Sun Lagrange point



July 6, 2015; Credit – NASA

2048 × 2048 pixels; nadir resolution 8 km.

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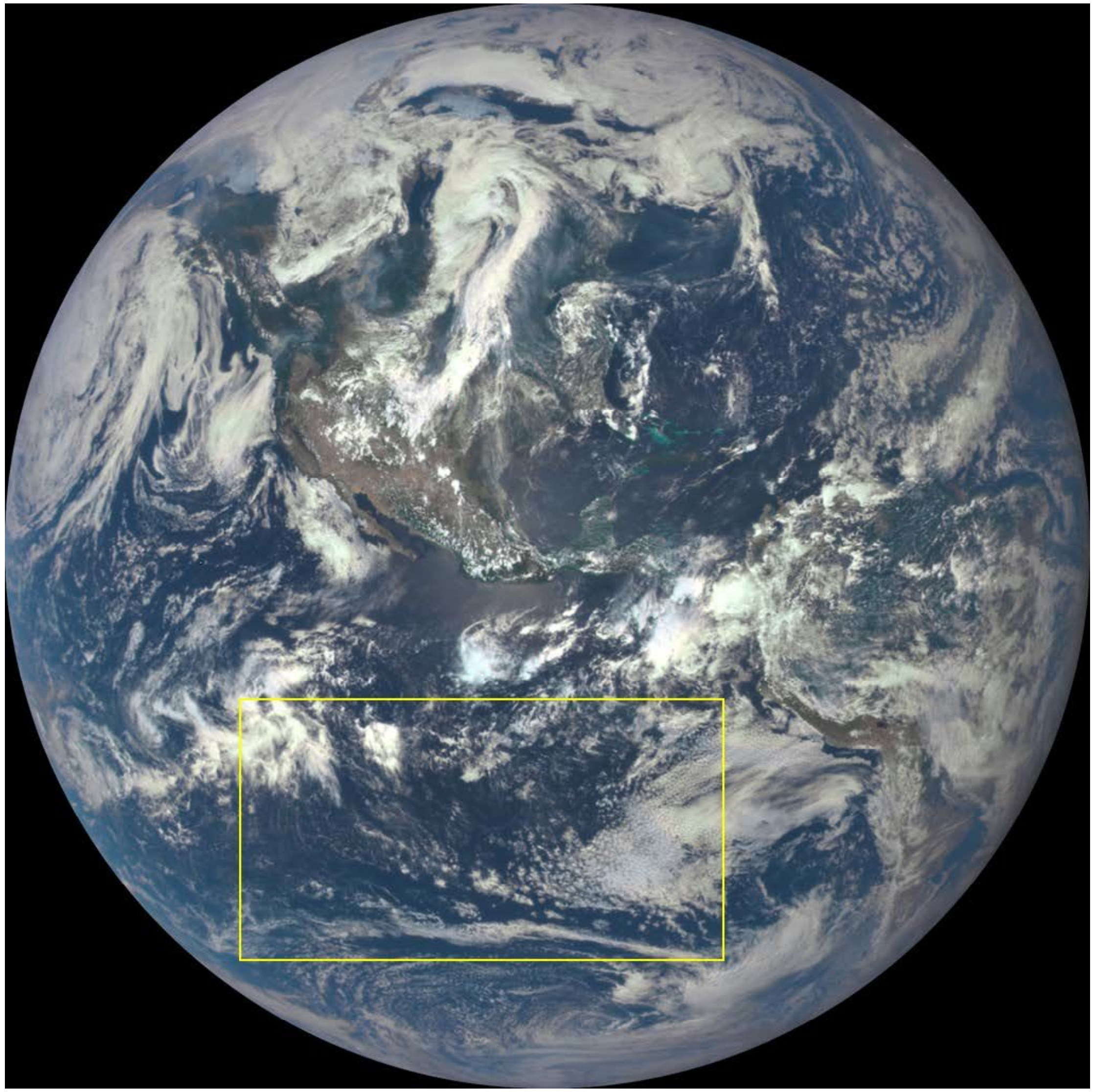
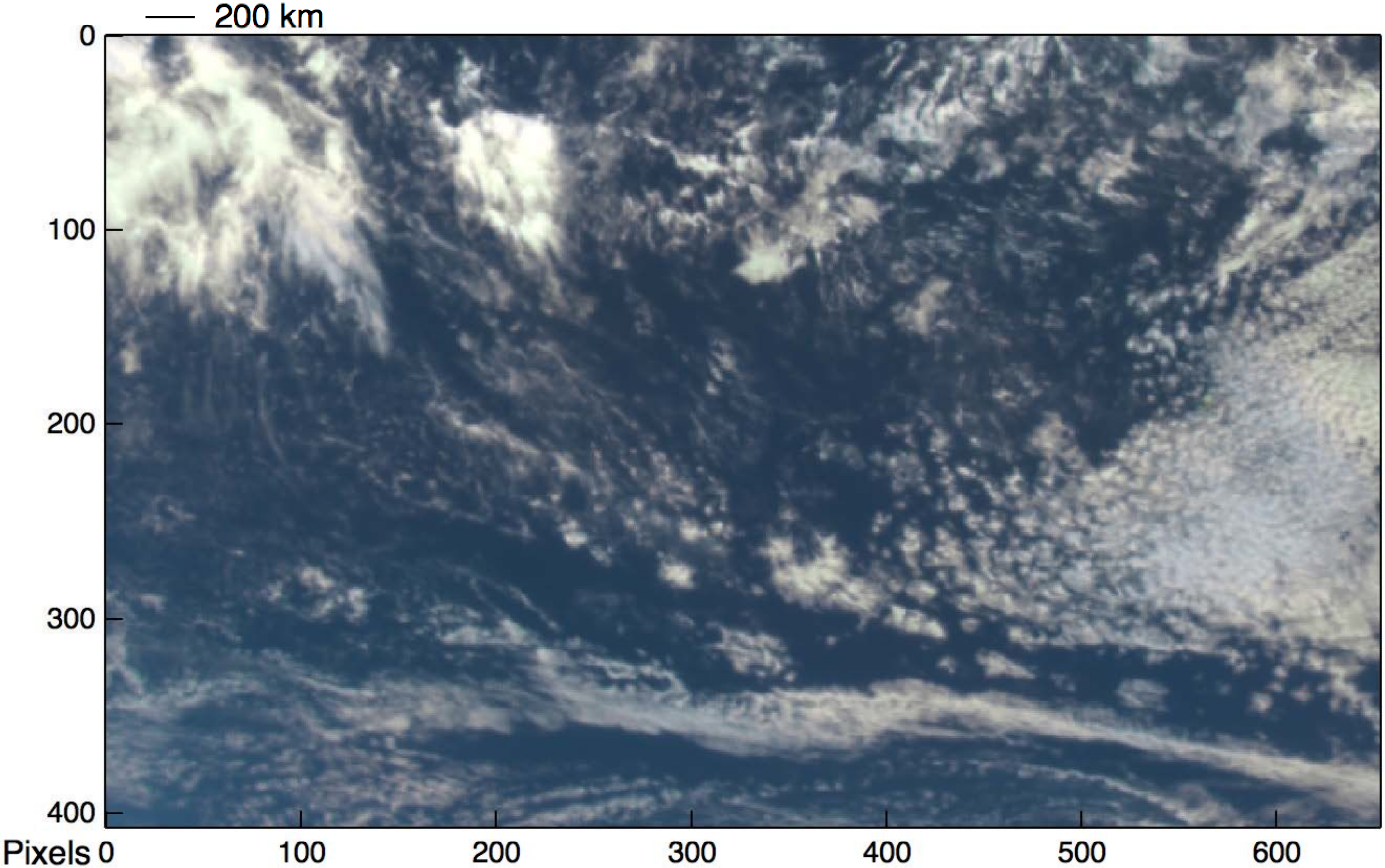


July 6, 2015; Credit – NASA

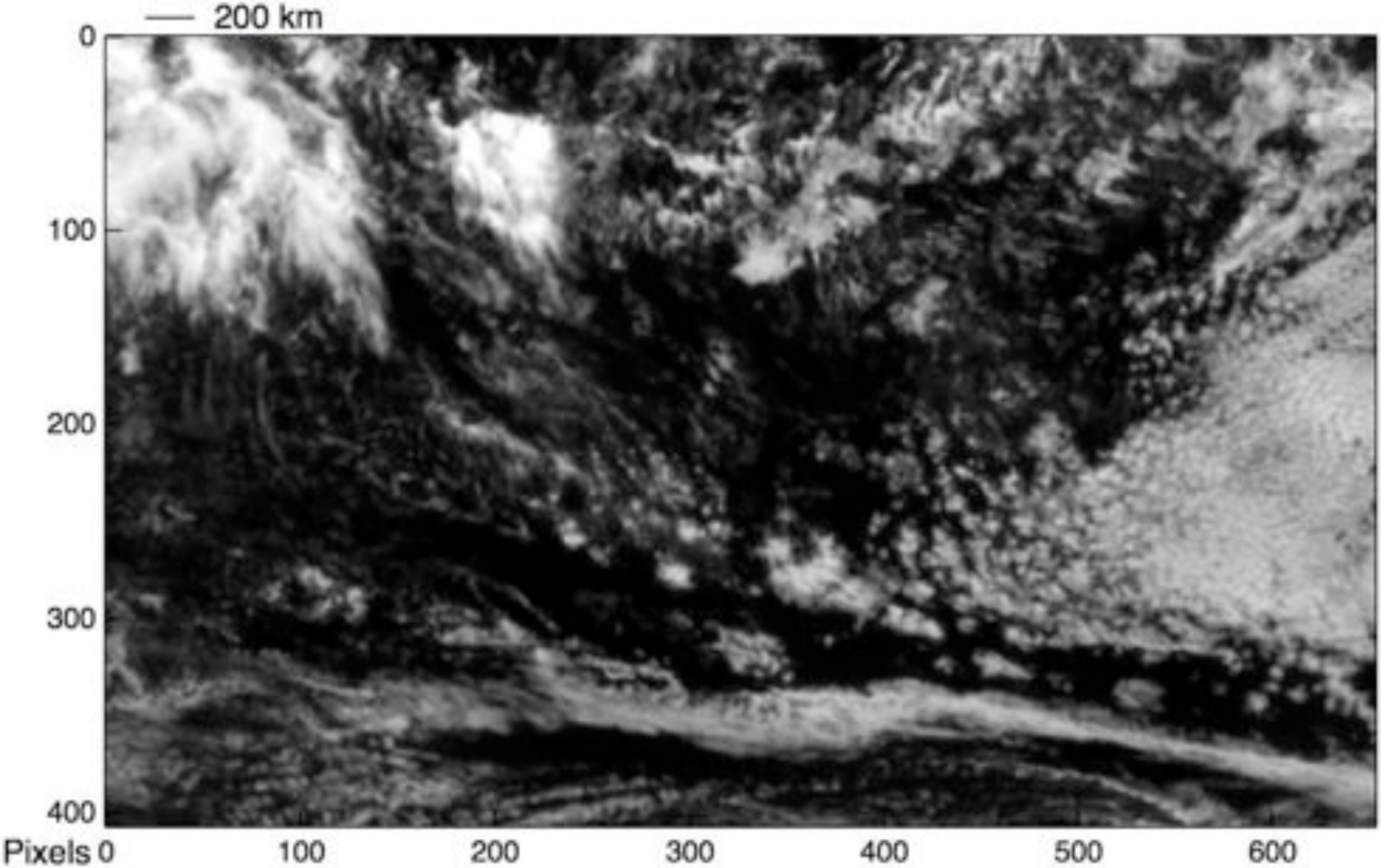
Focus in on a box over the southeastern Pacific.

SOUTHEASTERN PACIFIC AT NATIVE RESOLUTION



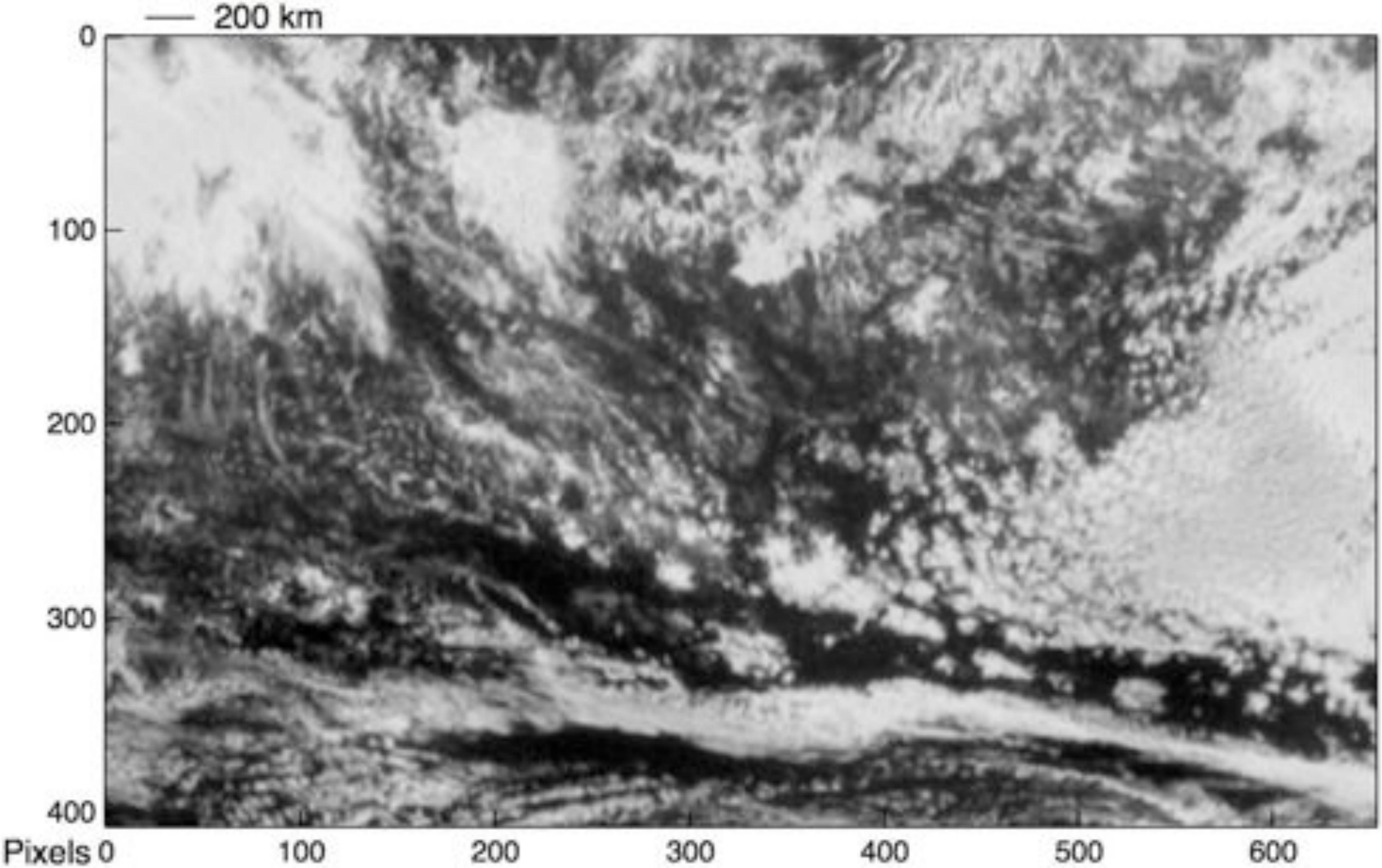
Rich structure in clouds at a variety of scales.

RED IMAGE



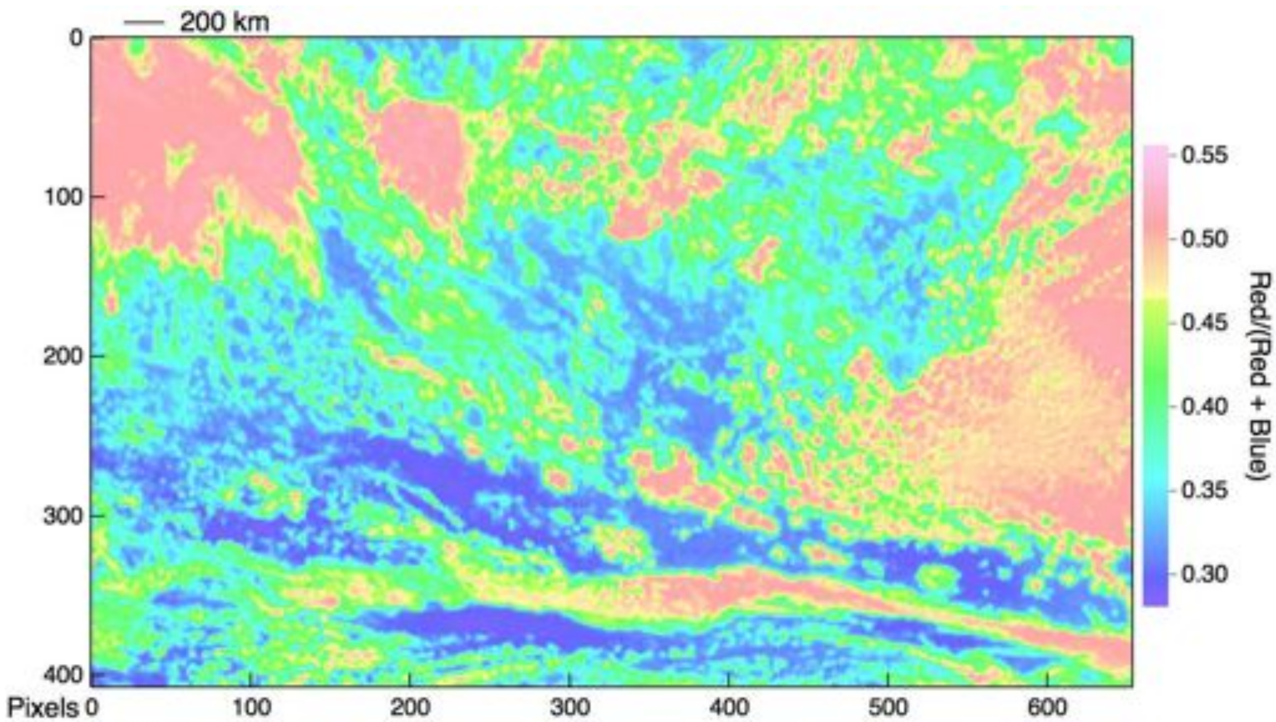
Red image emphasizes clouds (red filter in black and white photography).

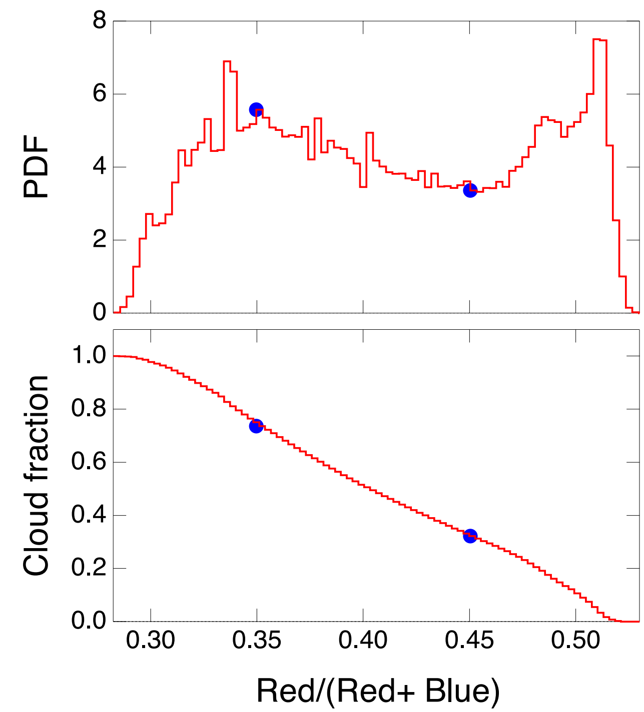
RED/(RED + BLUE) IMAGE – RRB



Red/(Red + Blue) normalizes for intensity and brings out thin clouds.

FALSE COLOR RED/(RED + BLUE) IMAGE





Red/(Red + Blue) normalizes red radiance and brings out thin clouds.

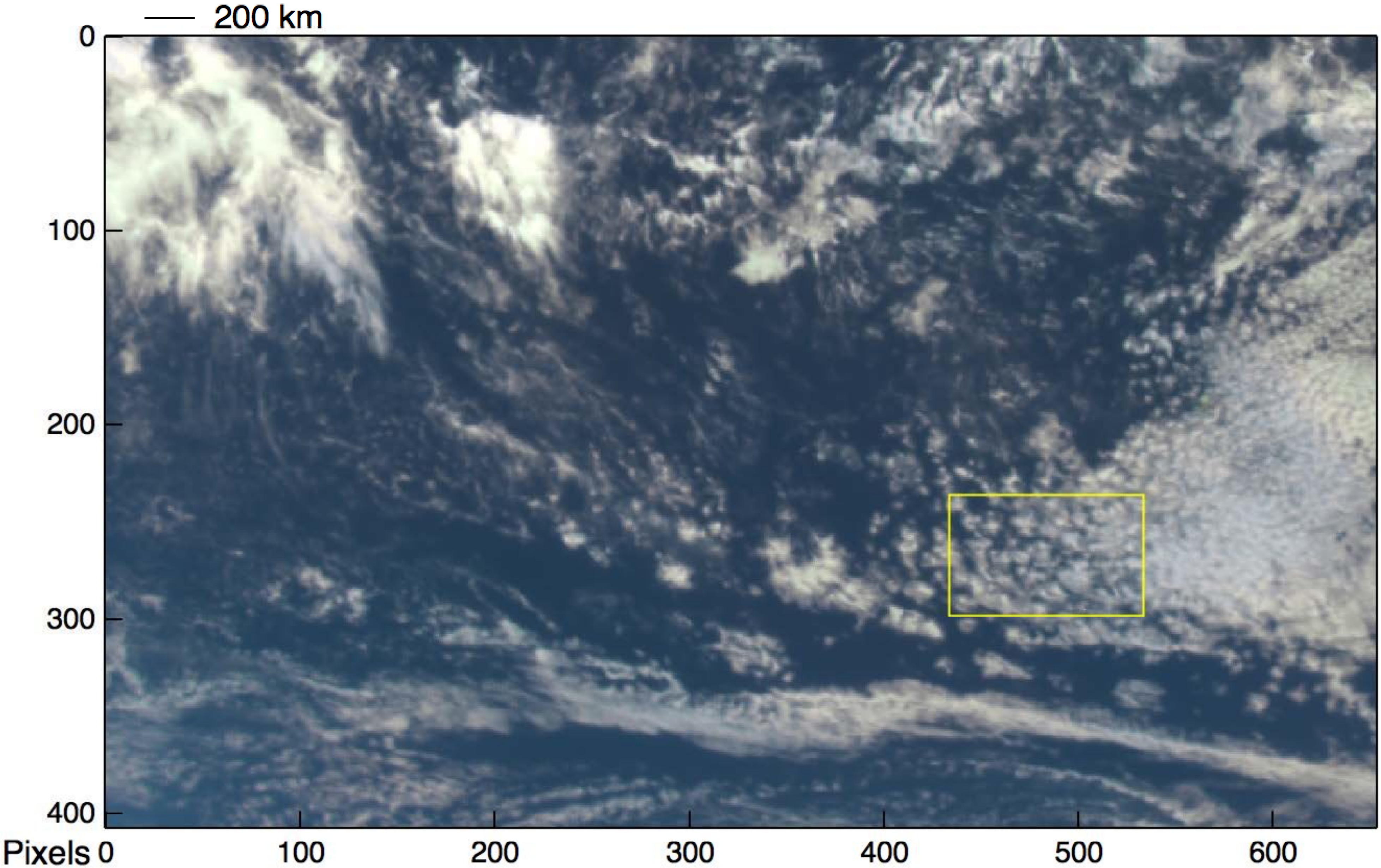
Pixels with RRB greater than ~ 0.45 are pretty confidently cloud; cloud fraction, evaluated from integral of PDF, ~32%.

Values of RRB less than ~ 0.35 are pretty confidently cloud free; cloud fraction ~ 73%.

Cloud fraction ranges from 32% to 73%.

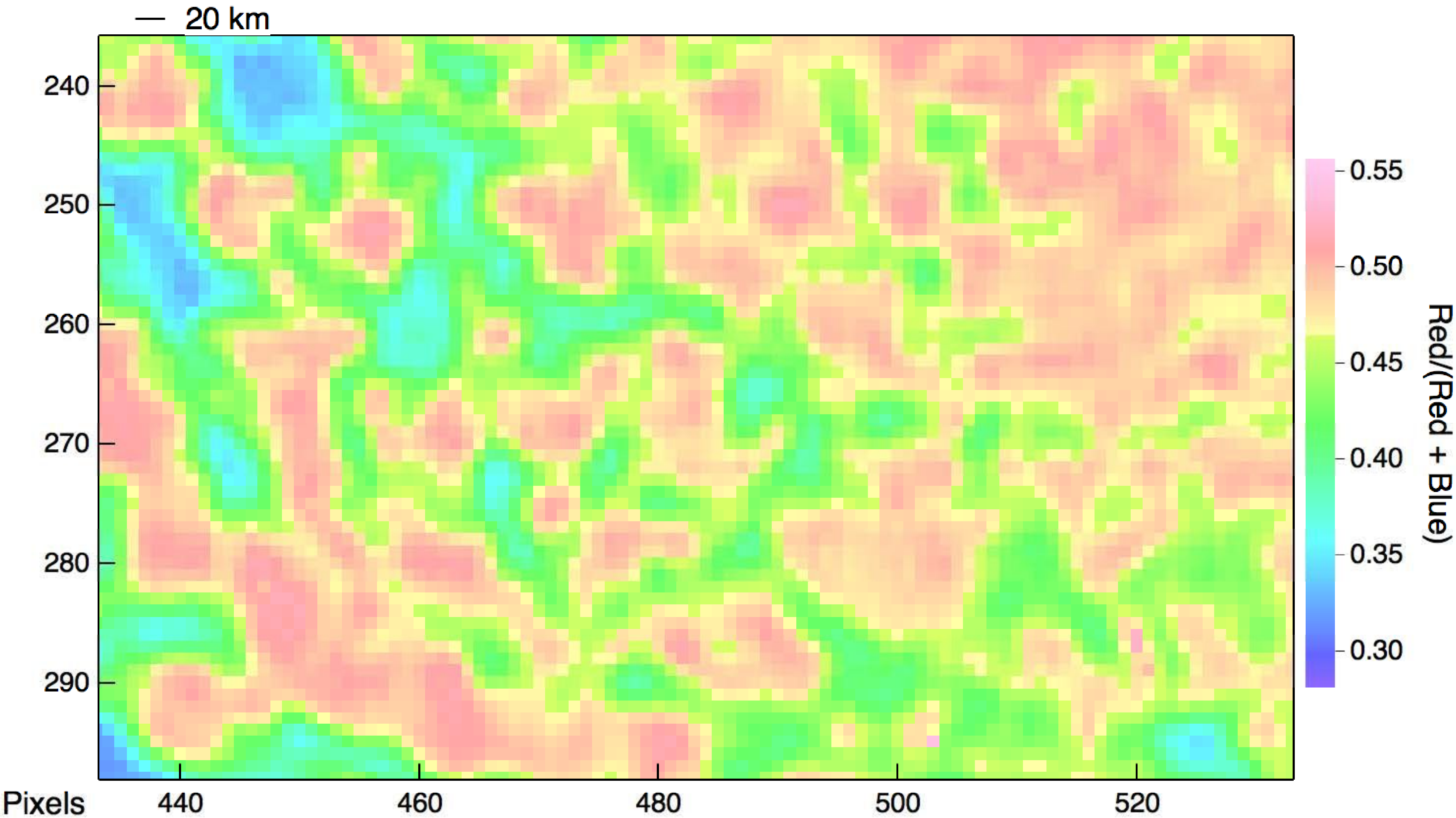
There is ***no value of RRB that uniquely separates cloud from clear sky***.

ZOOM IN ON POCKETS OF CLOSED CELLS



Organized convective cells contributing to planetary reflectance.

FALSE COLOR RED/(RED + BLUE) IMAGE



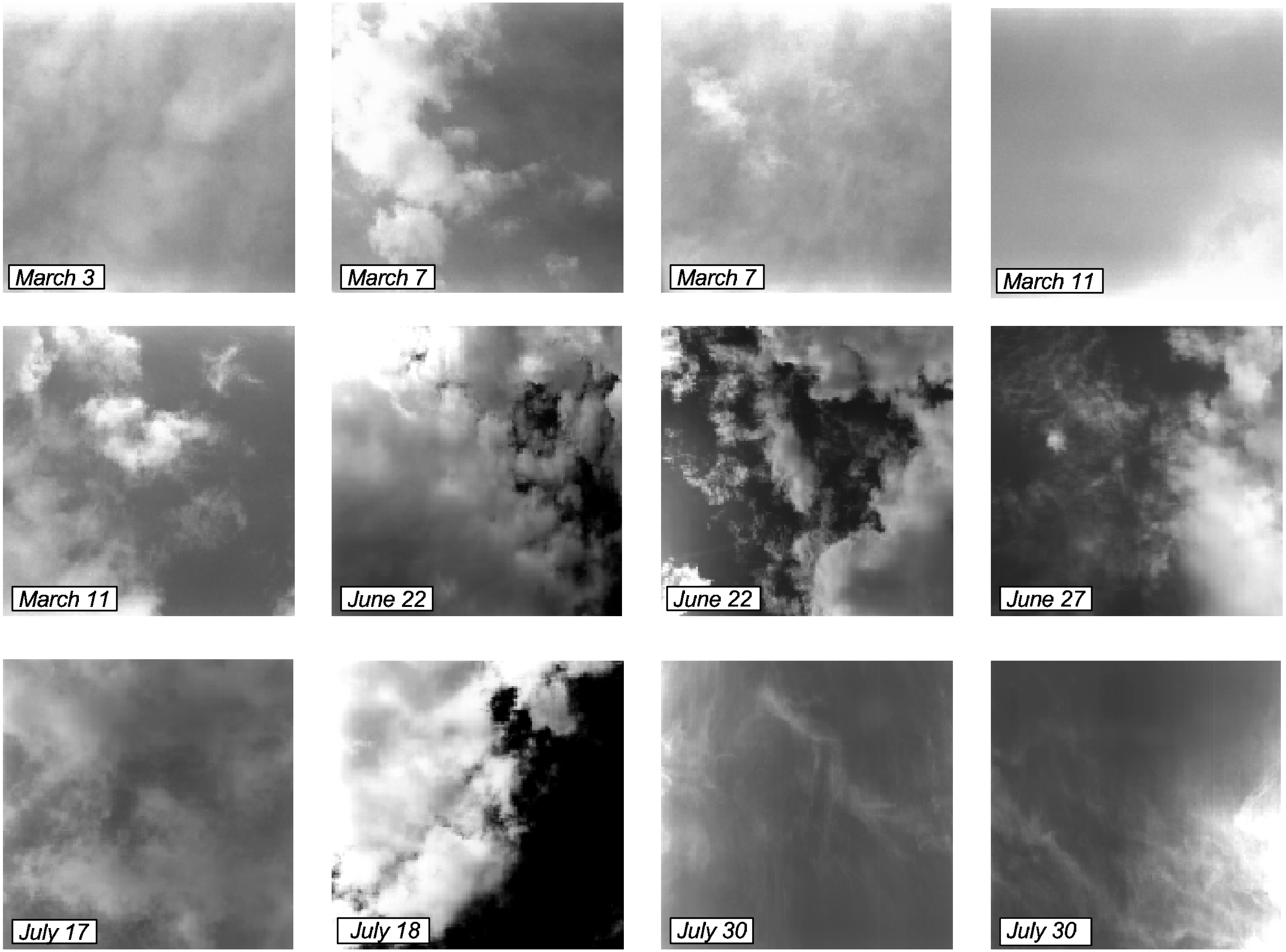
Note organized structure in RRB image.

CLOUD PHOTOGRAPHY FROM THE SURFACE LOOKING UPWARD

THE MULTIFRACTAL SCALING OF CLOUD RADIANCES FROM 1M TO 1KM

D. SACHS S. LOVEJOY and D. SCHERTZER

Fractals, Vol. 10, No. 3 (2002) 1–12



HIGH RESOLUTION IMAGER

Fujifilm FinePix S1

14 Megapixels 3456 × 4608

3 Color, RGB, 16 bit

1200 mm focal length
(35 mm equiv)

1 Pixel = 6 μrad (20 μrad)

FOV 22 × 29 mrad
(2 × 3 sun diameters)

Programmable

Wi-Fi communication

Weather resistant

$400

1200 mm EQUIVALENT FOCAL LENGTH

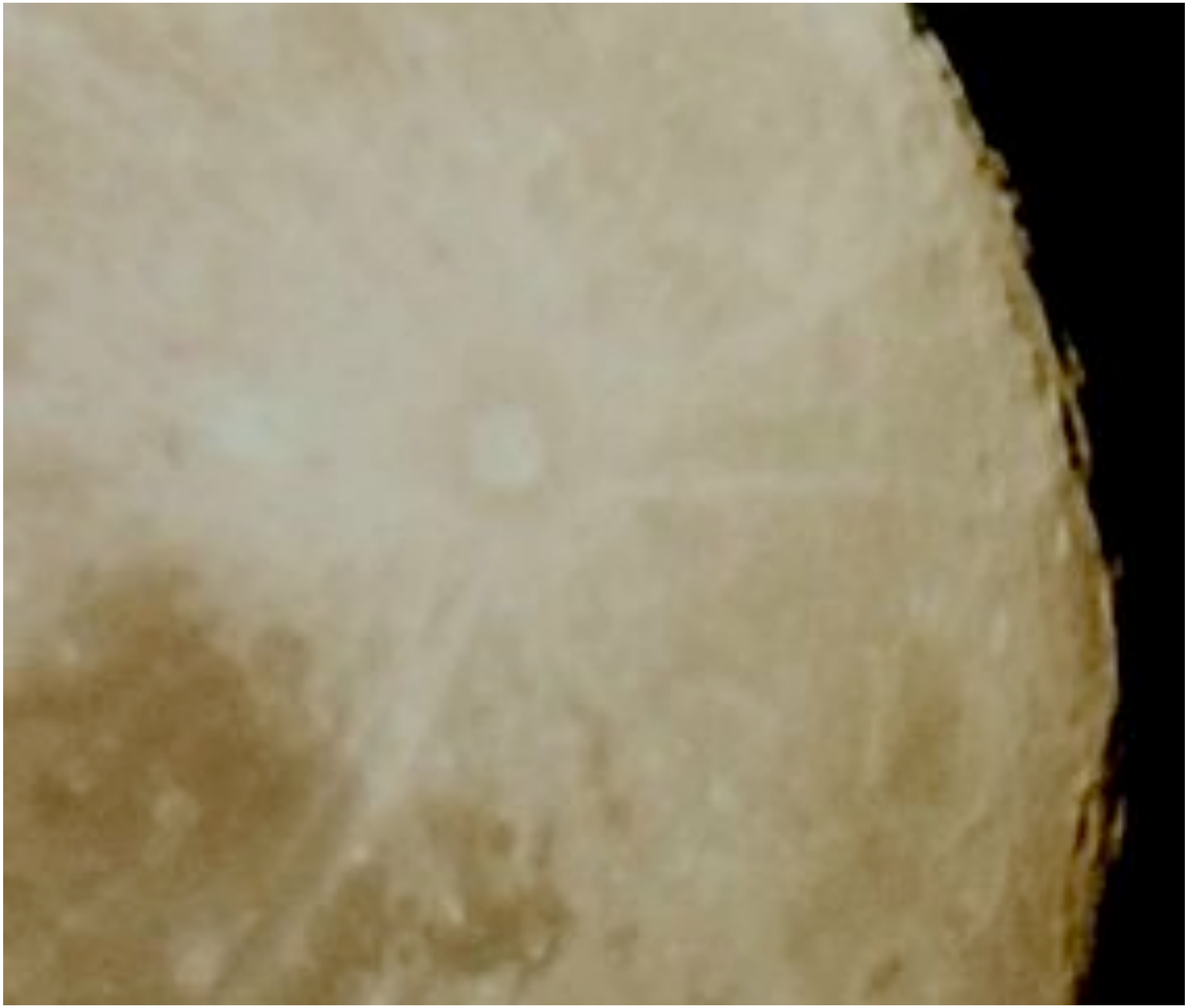
Todd Vorenkamp, B&H Photo, NYC

That's 1.2 meters!

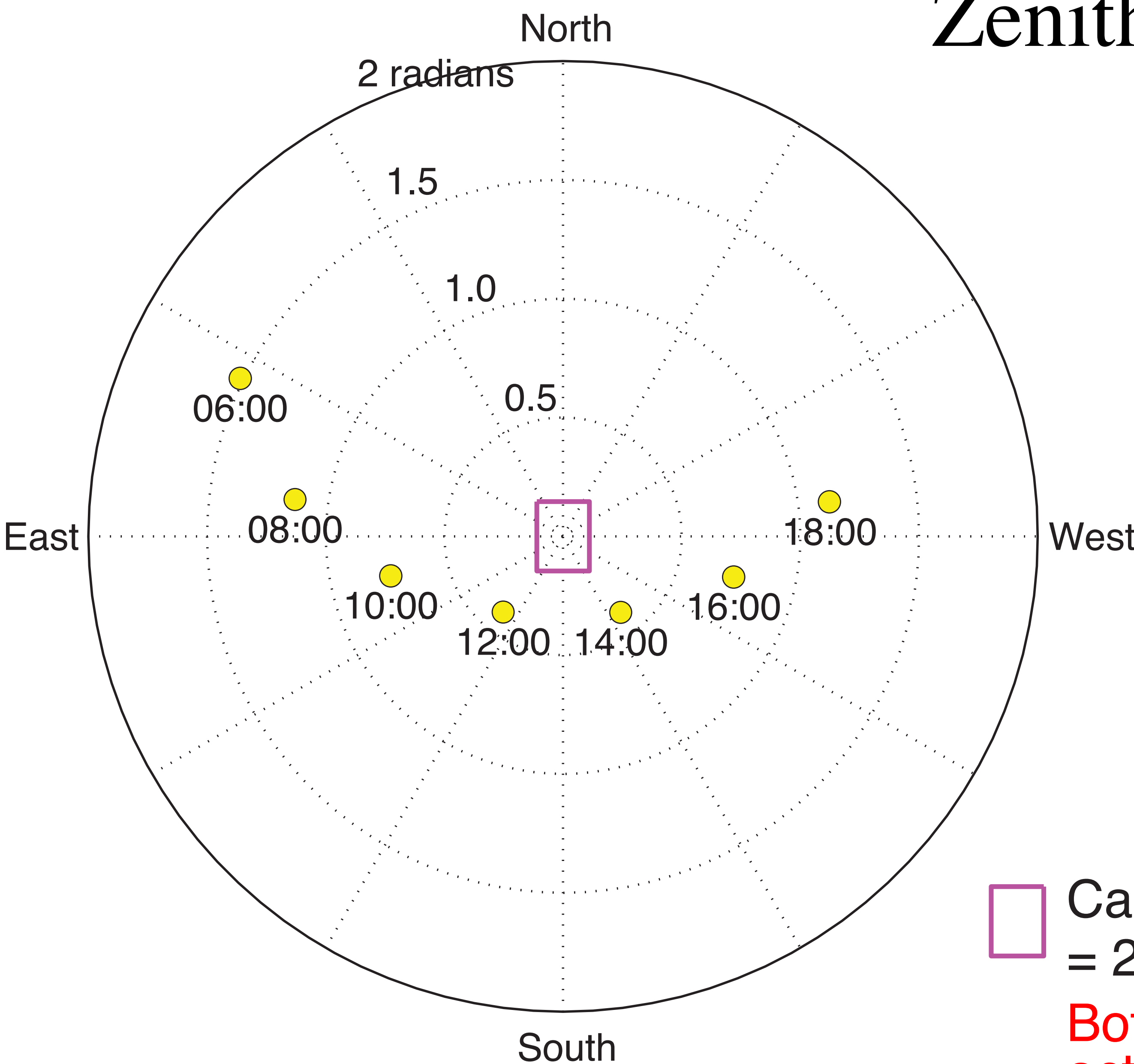
NARROW FIELD OF VIEW

29 × 22 mrad ≈ 3 × 2 sun (or moon) diameters, 29 × 22 m at 1 km

HIGH RESOLUTION



OBSERVATION GEOMETRY
Zenith looking



Solar zenith angle and azimuth, July 15, 2014, 6 am to 6 pm EDT
Upton, Long Island, NY

Sun, angular diameter $0.535^\circ = 9.3$ mrad

Camera FOV, 22 x 29 mrad = 2 x 3 sun diameters

Both drawn 10 times actual angular dimension

STRENGTHS AND ADVANTAGES

Black background of outer space: No surface effects (to first order).

No side-wall issues; no correction sky cover to ground cover.

Readily available ***data acquisition hardware and software***.

Available, easy-to-use ***image analysis and processing software***.

Lots of data!

WEAKNESSES AND LIMITATIONS

Two-dimensional only.

Daytime only.

Limited wavelength range.

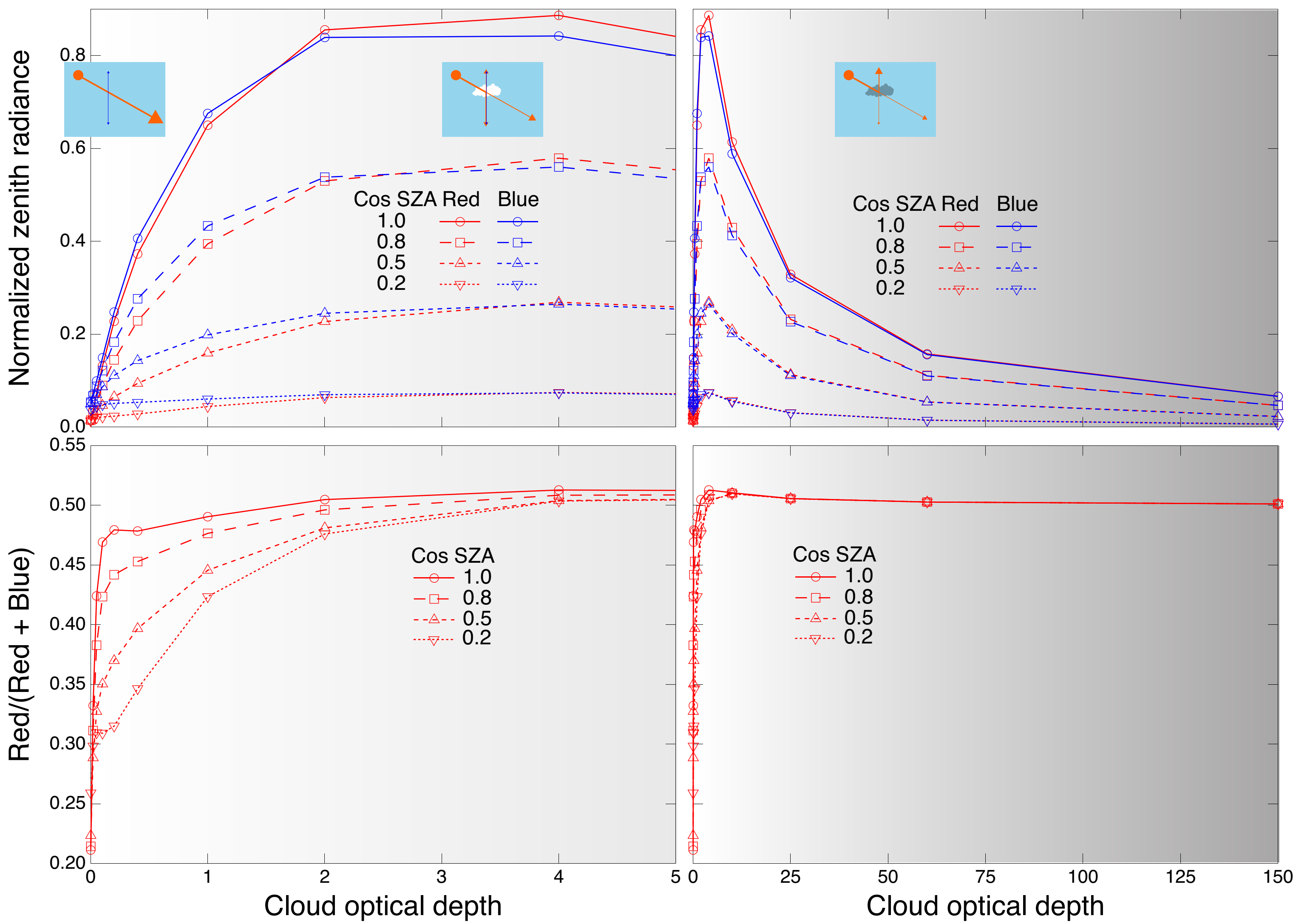
Small fraction of sky; ***extremely local***.

Aerosol masquerades as thin cloud.

Lots of data!

ZENITH RADIANCE AND RED/(RED + BLUE)

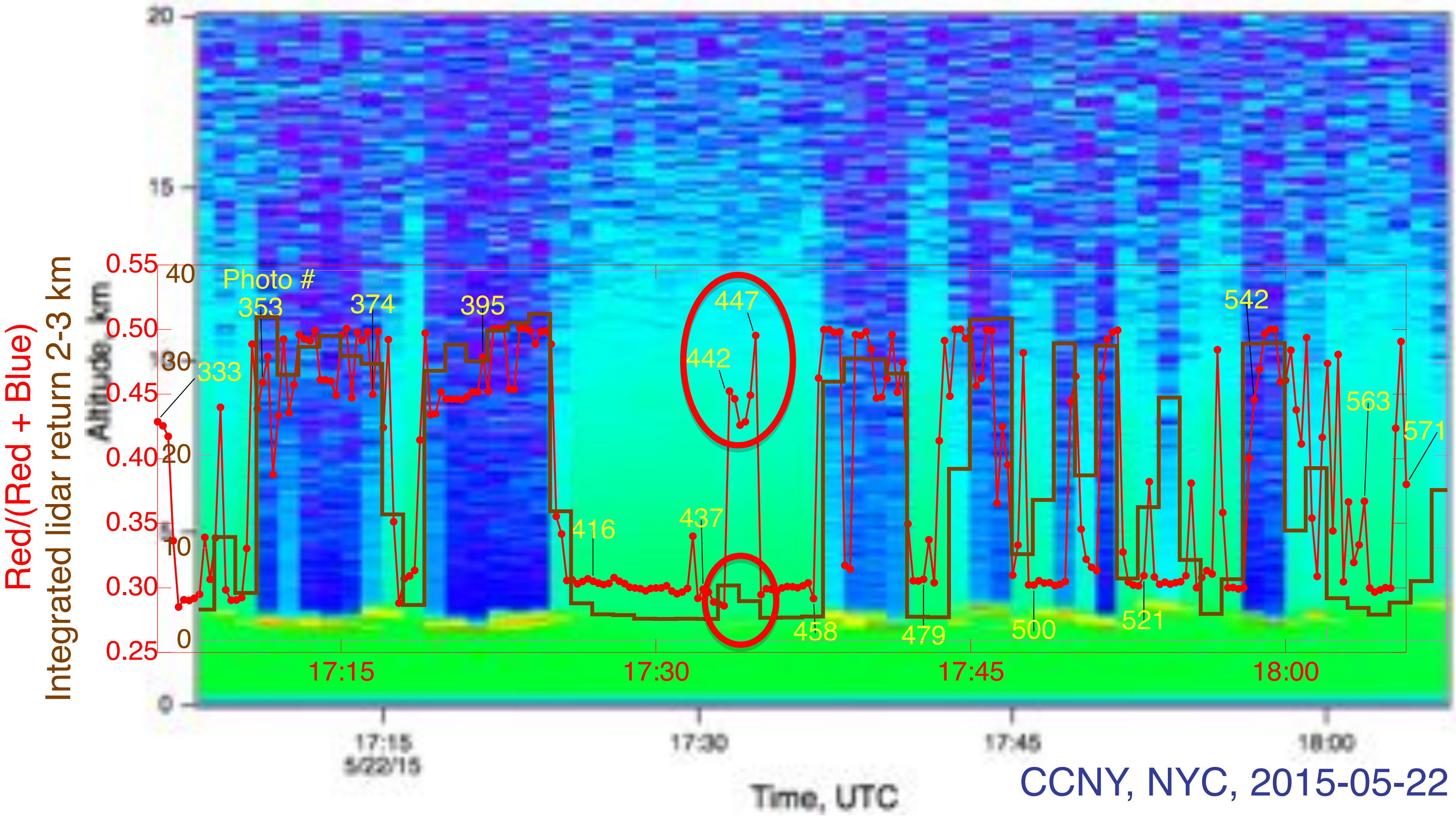
Dependence on cloud optical depth and solar zenith angle



Zenith radiance increases rapidly with τ, peaks, and then decreases.

RRB increases rapidly and then plateaus independent of solar zenith angle.

Lidar over same 1 hr period; superimposed integrated lidar signal and mean Red/(Red + Blue), RRB, from photos

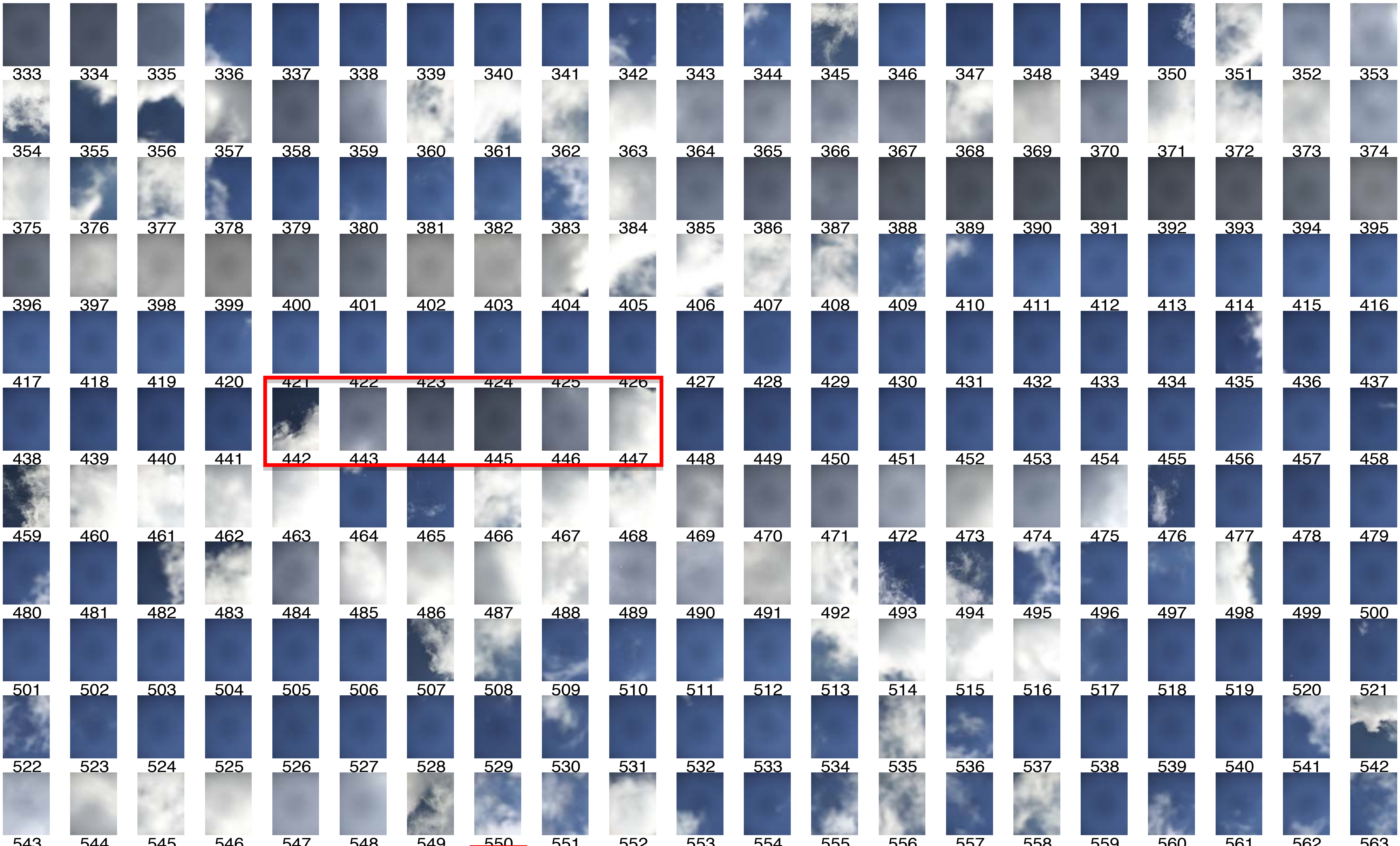


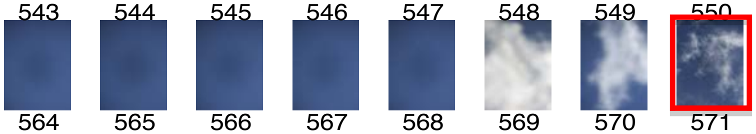
CCNY, NYC, 2015-05-22

Thin, single cloud layer, base ~ 2.6 km.
Note high RRB for cloud; low for clear.
Note high RRB even for very thin cloud, e.g. 442-447.
Could be broken cloud (442) or thin uniform cloud (443-447) more likely.
Note strong effect on RRB despite low optical depth inferred from transmittance.

SPATIAL AND TEMPORAL VARIABILITY

239 Successive photos at 15 s intervals over 1 hour, 2015-05-22, CCNY, NYC



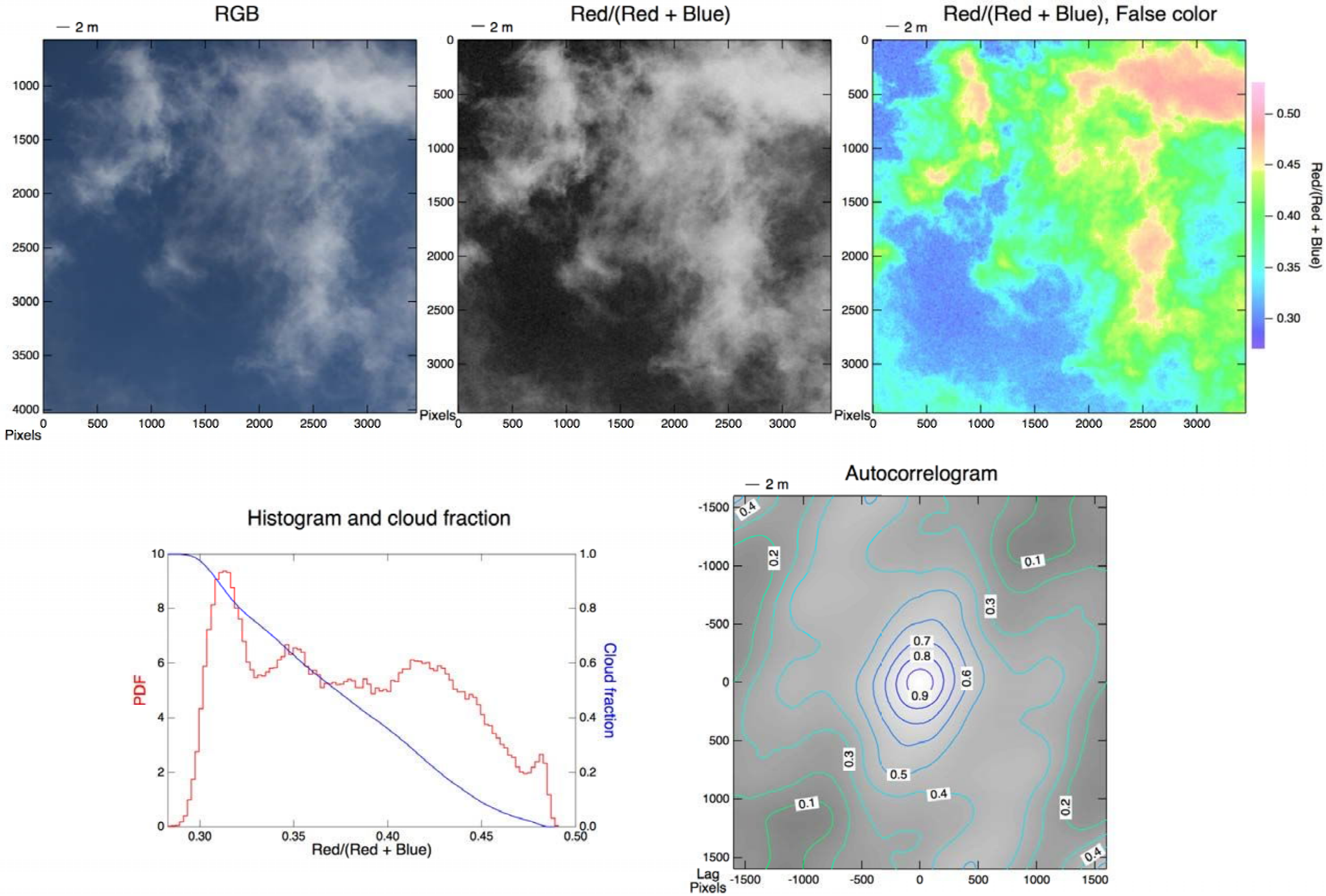


Note high variability at 15 s intervals.

Note high spatial variability; one image ~ 57 X 75 m

SPATIAL AUTOCORRELATION

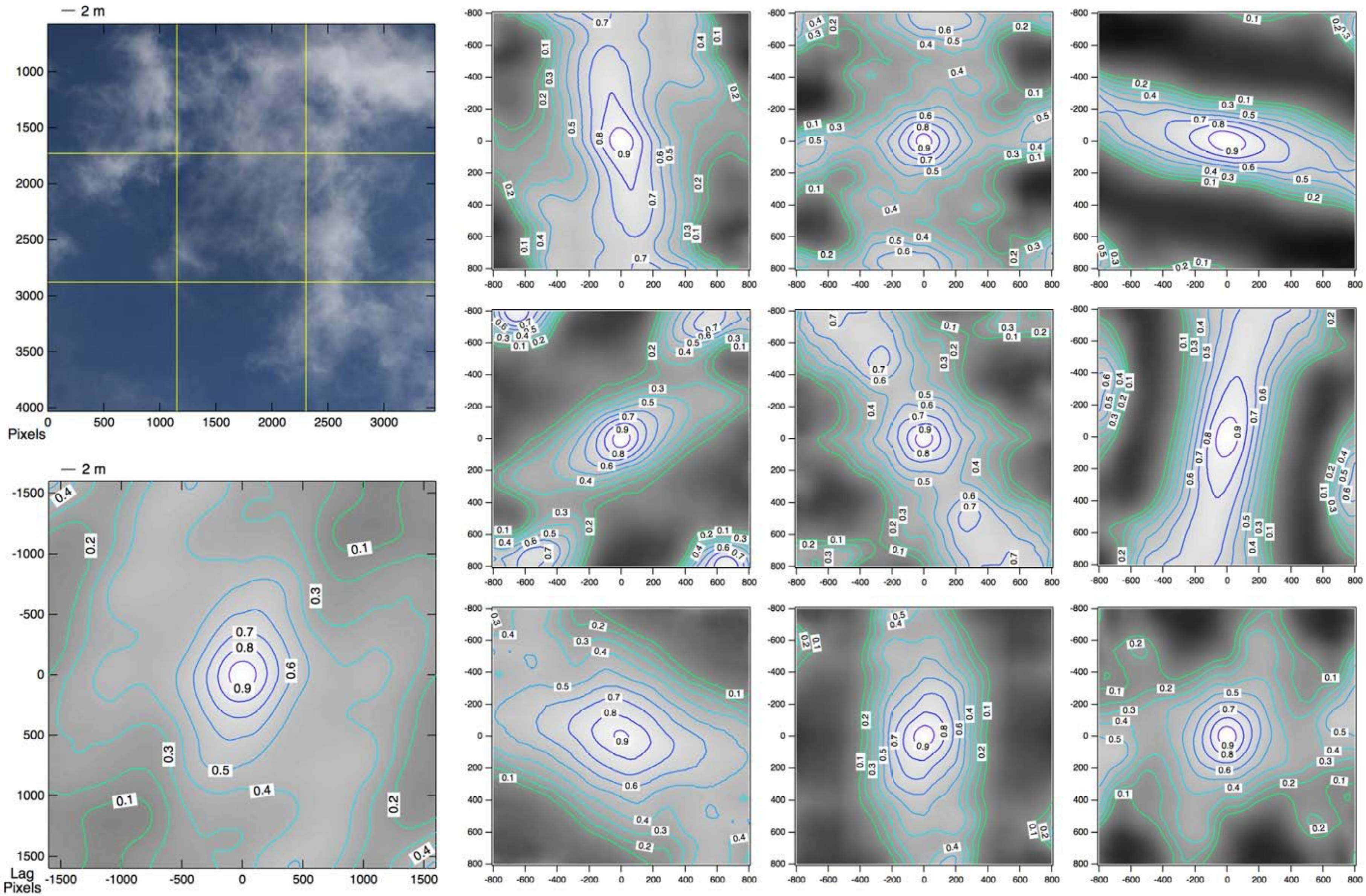
Broken single cloud, 2.6 km; NYC CCNY 2015-05-22



- No meaningful cloud fraction.
- Spatial autocorrelation reasonably symmetric with length ~ 15 m.

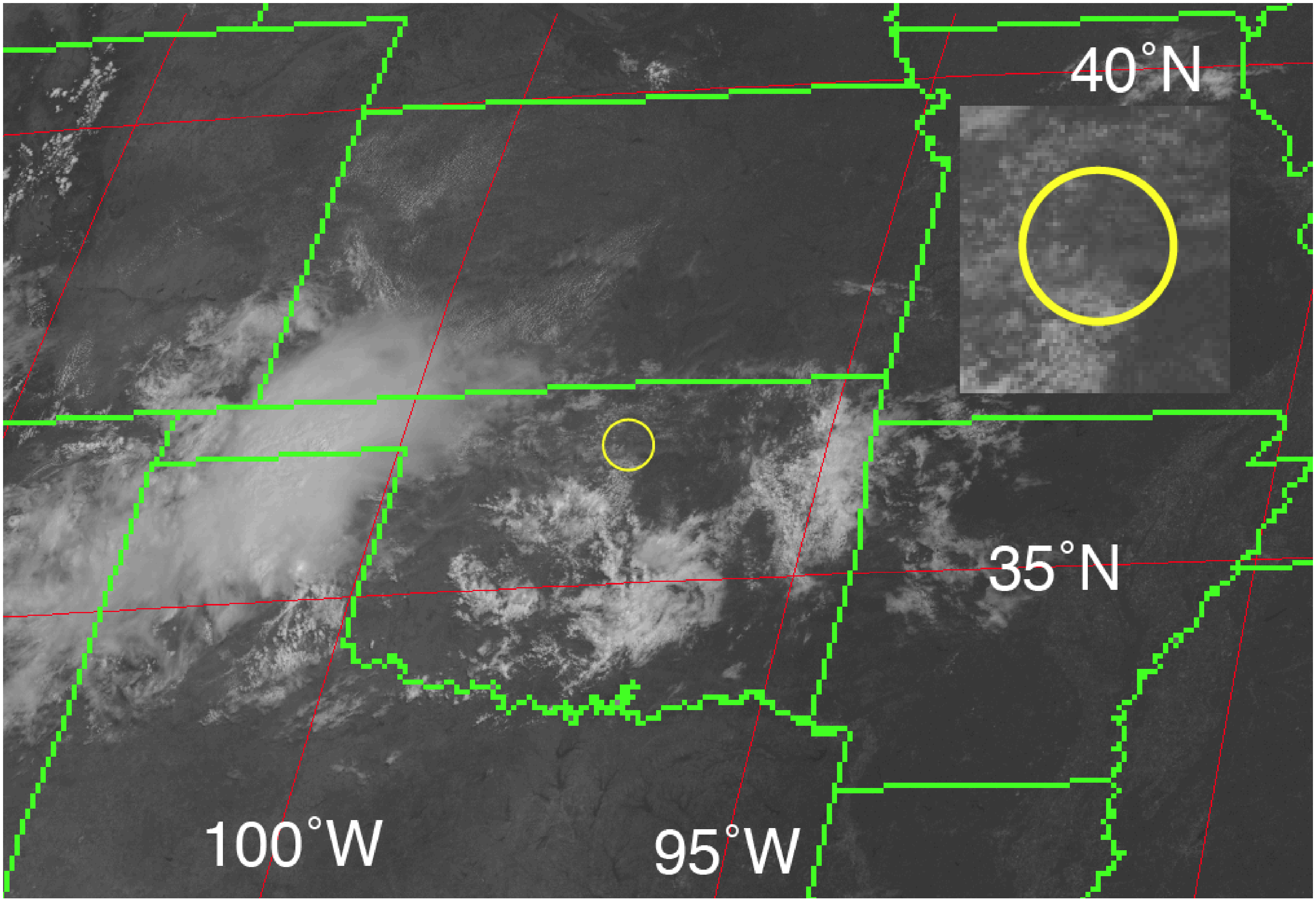
SPATIAL AUTOCORRELATION

Dependence on location within single broken cloud



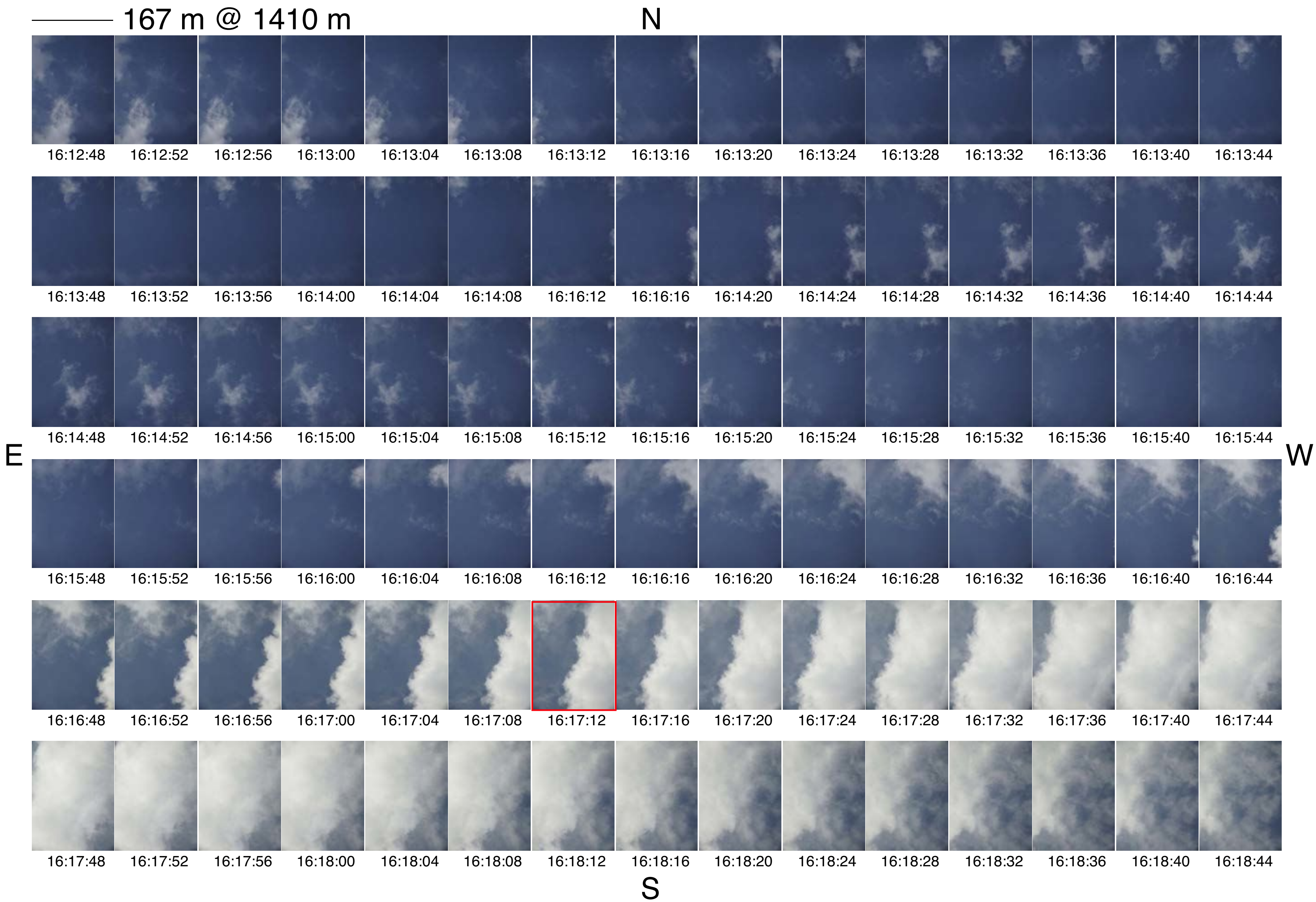
- Autocorrelation structure is highly variable within image.

GOES VISIBLE CHANNEL, SGP, 2015-0731, 1600 UTC



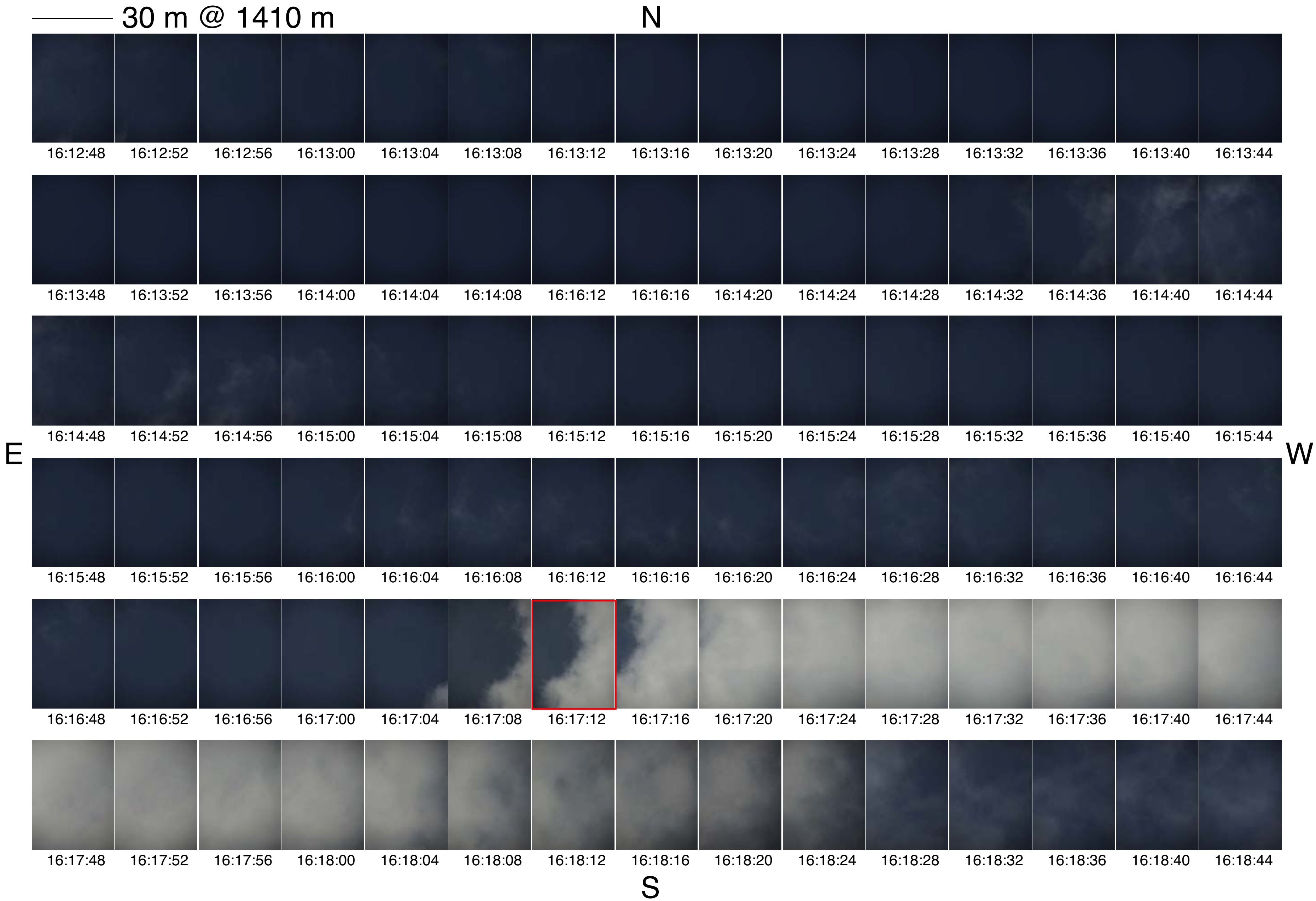
Thin broken clouds visible in 1-km resolution GOES image.

SIX MINUTES IN OKLAHOMA, JULY 31, 2015



Note general eastward motion with time; note also evolution of features.

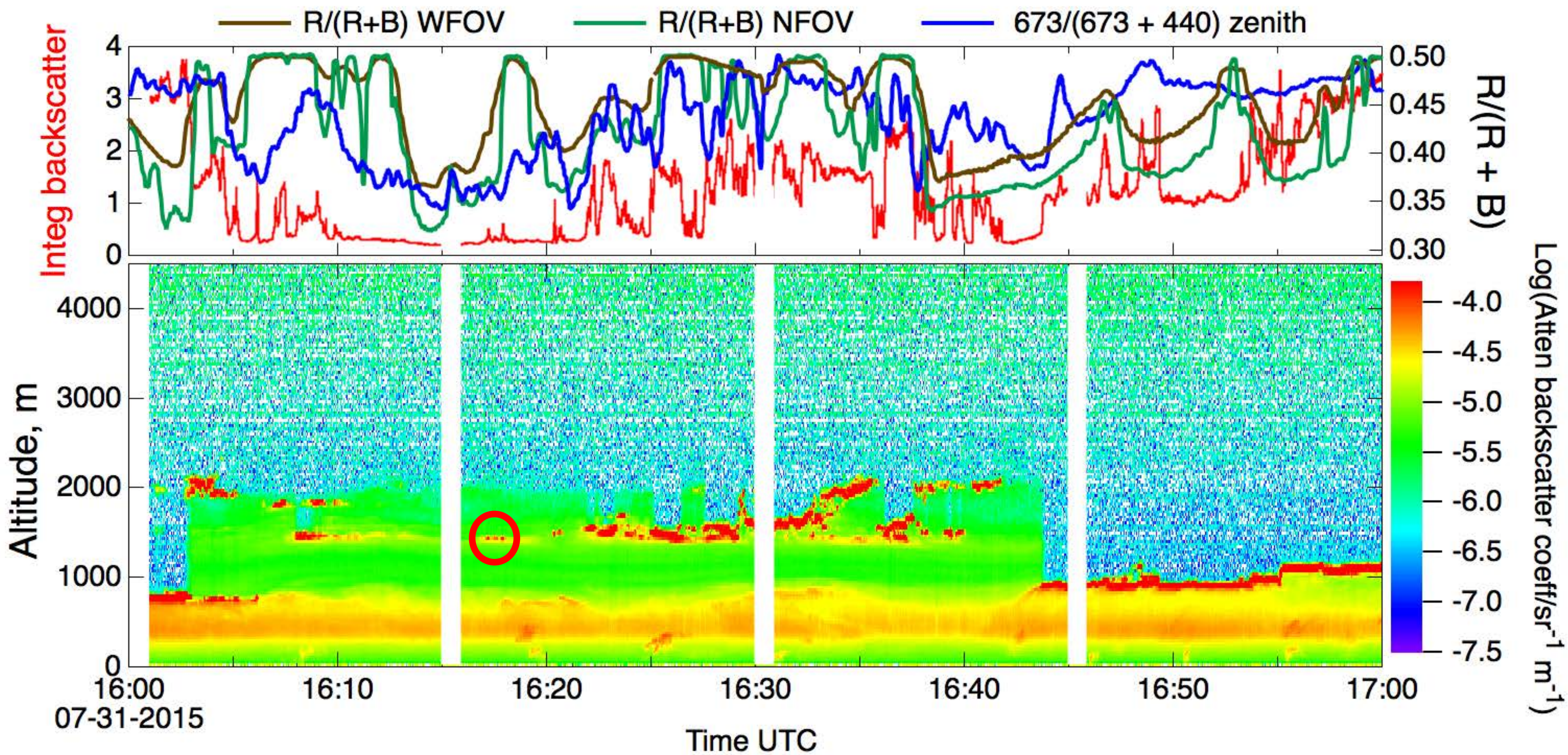
SIX MINUTES IN OKLAHOMA, JULY 31, 2015



Note temporal evolution and spatial inhomogeneity even at this scale.

MULTIPLE MEASURES OF CLOUD

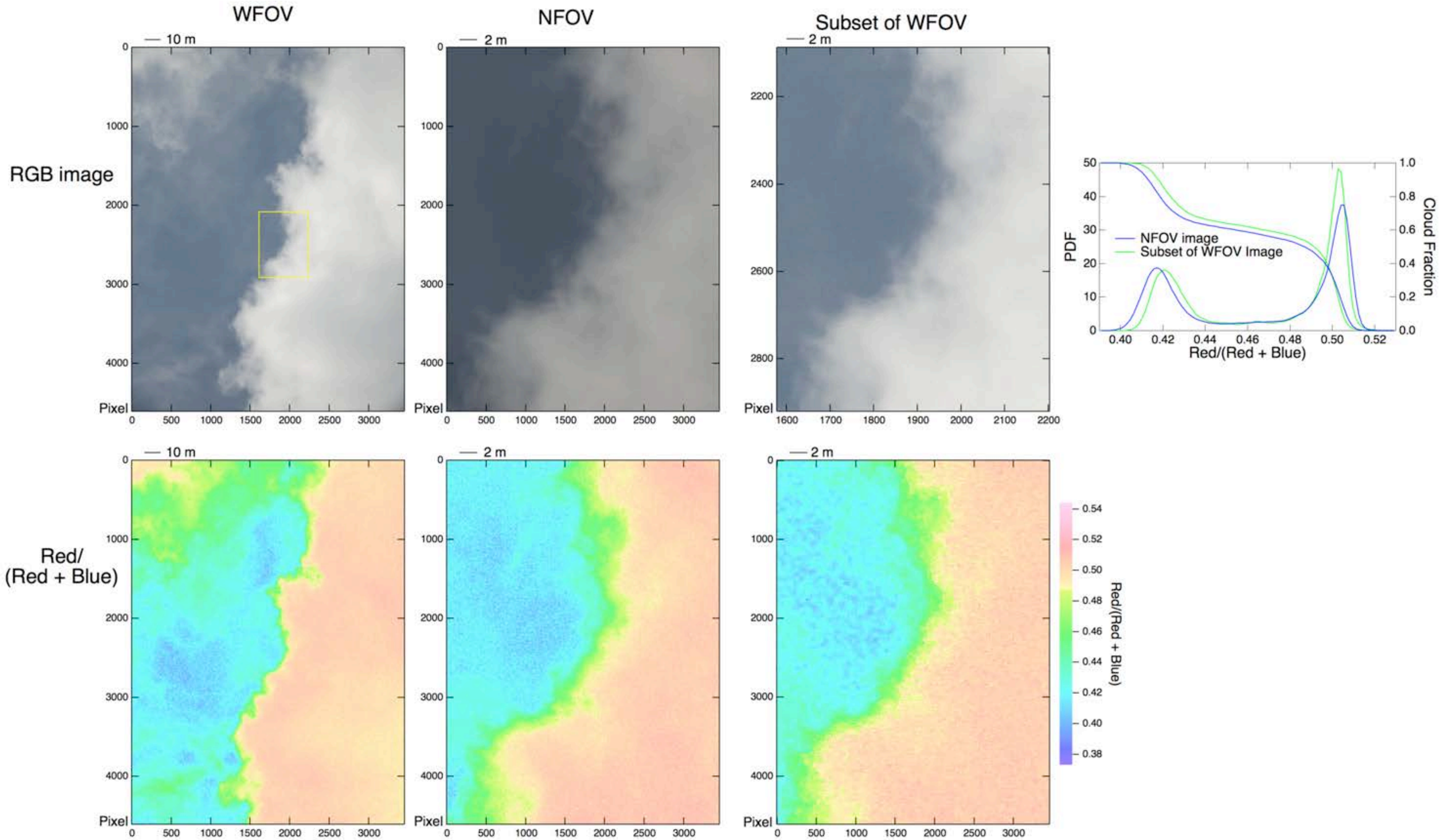
North central Oklahoma, 2015-07-31



Lidar gives cloud base height and measure of transmittance.
Integrated lidar return is measure of cloud amount.
R/(R+B) from two zenith pointing cameras: 21 × 29 mrad, 120 × 160 mrad.
673/(673 + 440) from zenith pointing spectral radiometer.
All measures show more or less coherent signals of intermittent clouds.

COMPARE WFOV AND NFOV IMAGES

Examine subset of WFOV corresponding to NFOV image



Red/(Red + Blue) false-color images and histogram are virtually identical for two images, showing ***robustness of quantity***.

STRENGTHS OF RED/(RED + BLUE) AS MEASURE OF CLOUDINESS

- Continuously variable quantity, as opposed to binary numerator in evaluating cloud fraction.
- Nearly monotonic in cloud optical depth τ, with plateau at large τ.
- Nearly independent of solar zenith angle, except at low τ.
- Nearly independent of scene brightness.
- Suitable for spatial and temporal averaging as $\langle R \rangle / \langle R + B \rangle$.

CONCLUSIONS

- Clouds can be imaged with ***resolution better than 1 meter*** by high resolution photography from the surface.
- Clouds frequently exhibit ***high spatial variability on scales of meters to tens of meters***.
- Even ***very thin clouds are readily detected by color*** and quantified as Red/(Red + Blue).
- Red/(Red + Blue) varies greatly for thin clouds. In scenes with variable cloudiness ***cloud fraction cannot be uniquely defined***.
- We are developing tools to model the radiance of such clouds and infer distributions of cloud optical depth and model cloud radiative effect.
- ***We welcome any suggestions*** for analysis of cloud spatial properties from photographic images.